

THE SNR G106.3+2.7 AND ITS PULSAR WIND NEBULA: RELICS OF TRIGGERED STAR FORMATION IN A COMPLEX ENVIRONMENT

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Draft version February 1, 2008

ABSTRACT

We propose that the pulsar nebula associated with the pulsar J2229+6114 and the supernova remnant (SNR) G106.3+2.7 are the result of the same supernova explosion. The whole structure is located at the edge of an H I bubble with extended regions of molecular gas inside. The radial velocities of both the atomic hydrogen and the molecular material suggest a distance of 800 pc. At this distance the SNR is 14 pc long and 6 pc wide. Apparently the bubble was created by the stellar wind and supernova explosions of a group of stars in its center which also triggered the formation of the progenitor star of G106.3+2.7. The progenitor star exploded at or close to the current position of the pulsar, which is at one end of the SNR rather than at its center. The expanding shock wave of the supernova explosion created a comet shaped supernova remnant by running into dense material and then breaking out into the inner part of the H I bubble. A synchrotron nebula with a shell-like structure (the “Boomerang”) of length 0.8 pc was created by the pulsar wind interacting with the dense ambient medium. The expanding shock wave created an H I shell of mass $0.4 M_{\odot}$ around this nebula by ionizing the atomic hydrogen in its vicinity.

Subject headings: ISM: H I — molecular data — polarization — radiation mechanisms: non-thermal — stars: formation — supernova remnants

1. INTRODUCTION

The extended radio continuum source G106.3+2.7 was first classified as a supernova remnant (SNR) by Joncas & Higgs (1990). This SNR was later described by Pineault & Joncas (2000) in more detail. They separated the comet shaped structure into a small head with high radio surface brightness and a large extended tail of low surface brightness. A gap in the atomic hydrogen apparently correlated with the SNR suggested a distance of about 12 kpc. This would give the SNR a length of 200 pc and they concluded that G106.3+2.7 is a supernova remnant in the late stage of its isothermal evolution.

At the northern edge of the head there is a small shell-like structure with a diameter of about $3.5'$. This source coincides with strong X-ray emission and the γ -ray source 3EG J2227+6122. It was interpreted as the bow shock nebula of a fast moving pulsar or a pulsar wind blown bubble (Halpern et al. 2001a). These authors estimate the distance as ≈ 3 kpc from X-ray absorption values. Subsequently this pulsar, PSR J2229+6114, was detected in radio and X-rays (Halpern et al. 2001b). It has a period of 51.6 ms and a rotational energy loss rate of $\dot{E} = 2.2 \cdot 10^{37}$ erg/s.

In this paper, by utilizing the data provided by the Canadian Galactic Plane Survey (CGPS), we analyze the possible relationship between the pulsar nebula and the supernova remnant. Since the number of known combined SNRs is rather low, such an analysis would improve our conceptual understanding on the interaction of a pulsar nebula with its environment.

2. OBSERVATIONS AND DATA REDUCTION

The observations discussed here form part of the CGPS, which is described in detail by Taylor et al. (2001). In carrying out the research presented here, we have used those parts of the CGPS database which derive from observations with the DRAO Synthesis Telescope (Landecker et al. 2000) and CO observations from the Five College Radio Astronomy Observatory (FCRAO) (Heyer et al. 1998). Angular resolution varies as $\text{cosec}(\text{declination})$ and therefore changes slowly across the final mosaics. Before assembly into a mosaic, the data for the individual fields are carefully processed to remove artifacts and to obtain the highest dynamic range, using the routines described by Willis (1999). Accurate representation of all structures to the largest scales is assured by incorporating data from large single antennas with data from the Synthesis Telescope, after suitable filtering in the Fourier domain. Continuum data are derived from the 408 MHz all-sky survey of Haslam et al. (1982), and from the 1.4 GHz Effelsberg survey (Reich et al. 1997). Single antenna H I data are obtained from a survey of the CGPS region made with the DRAO 26-m Telescope (Higgs & Tapping 2000). To improve the resolution of the 1420 MHz continuum observations we also included data taken from the NVSS (Condon et al. 1998). The NVSS map was convolved to the resolution of our CGPS data. The resulting map was subtracted from the CGPS map and the difference added to the original NVSS map. The final image has a resolution of $45''$.

3. THE STRUCTURE OF G106.3+2.7

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In Fig. 1 the radio image of G106.3+2.7 at 1420 MHz is shown. In the lower image the overall structure of the source is clearly visible. The major parts are a comet shaped structure with a diffuse extended tail of low radio surface brightness and a smaller more structured head with higher radio surface brightness. The upper image is an enlargement of the latter. The brightest feature is the “Boomerang” to the north, described by Halpern et al. (2001a). The point-like source just to its south is most likely an extragalactic source (Halpern et al. 2001a). The head itself shows two prominent features. There is a peak in the center, south of the extragalactic source and a shell-like structure on its southern boundary. Also visible is a diffuse bridge extending from the head to the pulsar nebula, suggesting an interaction of those structures. The SNR’s radio continuum emission has a spectral index of $\alpha \approx -0.57$ ($S \sim \nu^\alpha$) (Pineault & Joncas 2000). Neither the tail nor the head show significant spectral fluctuations. However, the pulsar nebula seems to have a flat radio spectrum (Halpern et al. 2001a). We obtained a flux density of 90 ± 5 mJy by integration of our 1420 MHz data. Together with a flux density of 80 mJy at 4850 MHz taken from Becker et al. (1991) we derive a spectral index of $\alpha = -0.1 \pm 0.1$ for the pulsar nebula. This confirms the flat radio spectrum proposed by Halpern et al. (2001a) and supports its interpretation as a pulsar-powered synchrotron nebula.

Fig. 2 displays a map of polarized intensity at 1420 MHz in greyscale together with white contours representing the total power radio continuum. We find linear polarization in all parts of the object. The tail has only a small number of polarized patches but these show high percentage polarization of up to 70 %. The head is polarized except for an area between the pulsar nebula and the center of the head where we also find a peak in total power emission. The head shows peak polarization of up to 70 %. The most prominent polarization feature, however, is the pulsar nebula with an integrated percentage polarization of 40 %. Parts of the radio continuum bridge to the pulsar nebula appear to be highly polarized. These high percentage polarizations indicate low depolarization between the SNR and us. The mean rotation measure towards the “Boomerang” and the SNR G106.3+2.7 is around $RM \approx -200$ rad/m². This high rotation measure results in Faraday rotation of $\approx 500^\circ$ at a frequency of 1420 MHz. Since we find only low depolarization on the “Boomerang” it requires a very small distance which makes this object a local phenomenon, probably within 2 kpc. If it was further away, beam depolarization would occur because of superimposed regions of differing Faraday rotation within the beam.

The large OB association Cep OB2, which is located at a distance of about 950 pc (Garmany & Stencel 1992), lies in the direction of G106.3+2.7 and partly overlaps with the supernova remnant. The members of this OB association ionize the material between them which leads to the depolarization of extended polarized emission from behind them at low radio frequencies. This gives us another upper limit for the distance to G106.3+2.7.

4. THE STRUCTURE OF THE COLD ENVIRONMENT

4.1. The head’s hydrogen envelope

In Fig. 3 we plot channel maps of our H I data cube representing an area around the head of G106.3+2.7 at low negative radial velocities. There is a shell-like H I structure around the eastern edge of the head best seen at -6.41 km/s but also quite prominent at -5.59 km/s and -7.23 km/s. A shell of H I is wrapped around the “Boomerang”, peaking at the same velocity as the shell around the head of the SNR. The coincidence in velocity clearly demonstrates that the SNR and the pulsar nebula are associated. This is the first time that an interaction between a pulsar nebula and cold interstellar material has been observed. It looks like the pulsar is either pushing the neutral hydrogen outwards or ionizing cold atomic hydrogen in its vicinity with its pulsar wind and thus creating the shell-like structure.

The center velocity of -6.4 km/s puts the SNR at a distance of 800 pc. At this distance the SNR has a length of 14 pc and a maximum width of 6 pc. The pulsar nebula is 0.8 pc wide. The small shell of atomic hydrogen contains about 0.4 M_⊙ and the bigger shell around the head about 5 M_⊙. This leads to densities of about 200 cm⁻³ within both structures.

Halpern et al. (2001a) calculated the foreground H I column density to be $N_H = 6.3 \cdot 10^{21}$ cm⁻² from the spectral fit to their X-ray data. Based on this value they estimated a distance of 3 kpc. We integrated the foreground H I column density from our data using $N_H[\text{cm}^{-2}] = 1.823 \cdot 10^{18} \int T_B(v) dv$ (Kerr 1968) with T_B representing the H I excess brightness temperature and v its radial velocity. The result is $N_H \approx 2 \cdot 10^{21}$ cm⁻². This equation, however, is only valid if the neutral hydrogen in the foreground is optically thin. Comparison of the brightness temperature of two strong point like background sources in the vicinity of G106.3+2.7 ($l = 105.68^\circ$, $b = 2.42^\circ$ and $l = 107.84^\circ$, $b = 2.31^\circ$) with their H I absorption profiles indicates that most of the foreground material is optically thick with opacities higher than 3. This easily explains the factor of 3 between the calculated foreground N_H and the one derived from the X-ray data.

4.2. The head’s molecular envelope

In Fig. 4 we plot channel maps of our CO data cube in the same area and at the same radial velocities as the H I data in Fig. 3. At the same velocities where we found the eastern hydrogen envelope there is a molecular envelope around the western edge of the head structure. But in this case we do not see the same structure in all channels. The location of the CO envelope is to the west at -5.6 km/s but rotates to the northwest at -7.2 km/s. Since around the eastern edge we find neutral hydrogen in all channels we can assume that the hydrogen completely surrounds this area. The CO, on the other hand, seems to be incomplete giving the expanding supernova remnant space to break through and form the smooth extended tail. The narrow shell of molecular material contains about 40 M_⊙ of molecular hydrogen assuming $N_{H_2}[\text{cm}^{-2}] = 2.3 \cdot 10^{20} \cdot T_{CO} \cdot \delta v$. Here N_{H_2} is the column density of molecular hydrogen, T_{CO} [K] is the CO brightness temperature and δv [km/s] is the velocity width of these structures.

4.3. The big picture

Fig. 5 shows an image of the entire region surrounding G106.3+2.7. The head of the SNR and its molecular and

atomic envelope are visible in the lower left part of the image as is the small shell surrounding the pulsar wind. Apparently these structures represent only a small part of the entire cold environment. There is a large bubble centered at $l \sim 106.1^\circ$ and $b \sim 3.1^\circ$, with an inner diameter of about 1° which translates to about 14 pc at a distance of 800 pc. The outer diameter is about 20 pc. At the northern and eastern edge of the bubble we find patches of molecular material. The supernova remnant has apparently created a little bubble at the lower left edge of the large bubble with its shock wave.

5. DISCUSSION

5.1. The creation of the cold environment

We suggest that a first generation of stars was formed in the center of the big H I bubble which at that time was a cloudy dense medium. With stellar wind effects and/or supernova explosions the large bubble was formed. However, some very dense cloudlets remained because they were too dense and probably also too far away from the location of the exciting stars. The fact that the remaining patches we observe are located at the outer edges of the bubble supports this, as does an H I structure surrounding the northeastern patch of molecular material, which is most likely the remains of dissociated molecular hydrogen at the surface of this cloud. Stellar winds and supernova explosions within the large bubble apparently also triggered the creation of the progenitor star of our SNR G106.3+2.7. At the time the progenitor star of G106.3+2.7 was formed, the environment most likely looked very much like the two northern patches of molecular material. The new born star was located inside this molecular environment. It was a massive star, probably an early B or an O-type star. The small bubble in the cold environment in which we now find the head of the SNR was either formed by the progenitor star's stellar wind or by the expanding shockwave of the supernova explosion itself.

5.2. A bow shock or a pulsar wind nebula

Usually pulsar nebulae are expanding inside a bubble created by the shock wave of a supernova explosion. In this case there is no material left to interact with, because all the matter has been swept up and carried away already. The pulsar in G106.3+2.7 is apparently interacting with its dense cold environment. In the following we investigate two possible scenarios leading to the shell-like shape of the “Boomerang” pulsar nebula.

5.2.1. The “Boomerang” as a bow shock nebula

Since the shape of the object bears a striking resemblance to a bow-shock structure, we first investigate the constraints which are imposed by the observations in order for this hypothesis to be viable. For simplicity, we assume that the explosion which caused the SNR took place near the center of the head component and resulted in the candidate pulsar getting a kick velocity which took it to its present position near the bow structure. In view of the observed morphology, we also suppose the motion to be nearly in the plane of the sky and neglect projection effects. The distance travelled, L , is comparable to the radius of the head component R_s , so we set $L \approx R_s$. Letting

t represent the pulsar travel time and SNR age in years, v_p the pulsar space velocity in km/s, and R_s in pc, we have

$$R_s \approx 1.0 \cdot 10^{-6} v_p t \quad (1)$$

The equality between the pulsar relativistic wind pressure and ISM ram pressure implies that

$$\frac{\dot{E}}{4\pi l^2 c} = n_o \mu m_H v_p^2 \Rightarrow \dot{E}_{36} \approx 6.2 \mu n_o l^2 v_p \quad (2)$$

Here n_o is the ambient number density in cm^{-3} , l is the distance between the pulsar and the apex of the bow shock in pc, and \dot{E}_{36} is the pulsar rotational energy loss rate in 10^{36} erg/s. SNR dynamics give us:

$$R_s = \begin{cases} 0.34 \left(\frac{E_{51}}{\mu n_o} \right)^{0.2} t^{0.4} & \text{for adiabatic expansion} \\ 1.4 \left(\frac{\epsilon E_{51}}{\mu n_o} \right)^{5/21} t^{2/7} & \text{for isothermal expansion} \end{cases} \quad (3)$$

Here the parameter ϵ is the ratio of thermal energy in the SNR to the initial explosion energy E_{51} [10^{51} erg].

The pulsar distance from the center of the head is about 1.5 pc, its distance from the apex of the bowshock is about 0.4 pc and its rotational energy loss rate $\dot{E} = 2.2 \cdot 10^{37}$ erg/s (Halpern et al. 2001b). With an estimated value of 0.3 for ϵ we get:

$$E_{51} \approx \begin{cases} 1.7 \cdot 10^{-8} v_p & \text{adiabatic case} \\ 1.2 \cdot 10^{-6} v_p^{0.2} & \text{isothermal case} \end{cases} \quad (4)$$

Any reasonable value for the pulsar velocity (100 km/s $\leq v_p \leq$ 1000 km/s) will give us by far the lowest ever recorded explosion energy for the supernova explosion. Allowing for inclination effects or substantial variations in the observed parameters still leaves us with highly unlikely values of the energy parameters.

5.2.2. The “Boomerang” as a pulsar wind nebula

As an alternative, Halpern et al. (2001a) have suggested that the bow-shaped structure can be confined by the thermal pressure of the surrounding medium. This is indeed possible, but it implies an anomalously low velocity for an object belonging to a high-velocity class. The fact that the spectral index is flat makes it almost unavoidable that the emission originates from the relativistic pulsar wind itself. However we believe that the confinement is simply achieved because the relativistic wind is encountering the dense SNR shell in the northeast. In our picture the SN explosion took place at or very near the present position of the pulsar. In the northeast the shock has been quickly decelerated by its encounter with a relatively nearby and particularly high density medium, whereas towards the south it has expanded into a moderately dense medium (SNR head component) while breaking out in the southwest into a region of much lower density and giving rise to the tail component.

The morphology of the head and the tail structure supports this hypothesis. The head shows only the “Boomerang” and the southern shell as indications for the encounter of a shockwave with dense material. We do not find a shell structure towards the east of the head but we find an H I shell all around the east and the south of the

head. We can explain this by moving the location of the explosion to the current position of the pulsar. To the north and to the east the shockwave is running into dense material. The first free path for the shockwave is to the southeast where the southern shell begins. Another point for this scenario is that the distance between the location of the supernova and the shell to the south is now larger than its distance to the beginning of the tail, which should be expected in our picture. If the explosion occurred in the center of the head this would not be the case.

What seems peculiar however is the fact that the little bow-shaped shell in the north does not show enhanced non-thermal radio emission. This would appear to go against the expected view that an SNR should be brighter where the blast wave is moving against dense regions of the ISM. A similar situation has been encountered by Pineault et al. (1997) in their analysis of the CTA1 SNR. These authors argued that, in overdense regions where the shock velocity is considerably reduced, the Fermi acceleration mechanism (Bell 1978) might either be too slow or simply break down. The time efficiency can be quantified by evaluating the timescale τ_{acc} for acceleration of an electron to energy E , given by $\tau_{\text{acc}} \propto E/Bv^2$ (Ellison et al. 1990; Reynolds 1996). Hence either a low shock velocity or low ambient magnetic field, or a combination of both may imply that the electrons radiating at a given observing frequency ν , where $E \propto (\nu/B)^{1/2}$, are not yet present in the energy distribution. An alternative approach is to consider the growth and decay rates of the Alfvén waves responsible for the repeated scattering of the relativistic particles back and forth across the shock (Bell 1978; Blandford & Ostriker 1978). On one hand, the growth rate is proportional to the shock velocity and thus decreases as the shock slows down and, on the other hand, the decay rate depends on the first power of the number density of neutral atoms. Again this means that the acceleration mechanism may be quenched whenever the shock wave encounters sufficiently dense clouds. It is also possible that a thin steep (spectral index of order -0.5) non-thermal layer is present but not detectable because of beam smearing.

The interpretation of the tail component as resulting from a breakout of the SNR shock wave is also compatible with theoretical predictions. The numerical studies of breakout by Tenorio-Tagle et al. (1985) have shown that the asymptotic ratio of the velocity of the material breaking out into a region of lower density to that of the shock wave still propagating into the original medium could be expressed as

$$B_{\infty} = 4.22 - 1.89 (\log_{10} \lambda + 2), \quad (5)$$

where $\lambda \leq 1$ is the ratio of the densities. The same ratio at any normalized time $\tau = t/t_b$, where t_b is the time at which breakout occurred, was shown by Pineault et al. (1987) to be satisfactorily represented by the approximate analytical relation

$$B(\tau) = B_{\infty} - (B_{\infty} - 1)/\tau. \quad (6)$$

It follows from this relation that the ratio $r = L_t/R_s \approx B_{\infty}$ where L_t is the length of the tail component, as long as $\tau \gg 1$. Using $R_s \approx 3$ pc and $L_t \approx 12$ pc gives us a value of 4 for r . The length of the tail is difficult to determine since there is no sharp outer boundary. The

observed value implies $\lambda \approx 0.01$. A value of 8 for r would correspond to $\lambda \approx 10^{-4}$. It can also be shown that the breaking out material attains a maximum velocity

$$v_{bm} = v_b [0.35 B_{\infty} (B_{\infty}/(B_{\infty} - 1))^{0.6}] \quad (7)$$

at $\tau_m = (8/3)(1 - 1/B_{\infty})$, where v_b is the velocity just before breakout. For $B_{\infty} = 4$, the maximum velocity is about $1.7 v_b$. Assuming that the age of the SNR is comparable to the characteristic age of the pulsar we take $t \approx 10460$ yr (Halpern et al. 2001b). For an adiabatic expanding SNR we derive $E_{51}/\mu n_0 \approx 4.9 \cdot 10^{-4}$. With a density of $n_0 \approx 100 \text{ cm}^{-3}$ the explosion energy would be $E \approx 7 \cdot 10^{49}$ erg. Usually the characteristic age of a pulsar is higher than its real age which means the calculated explosion energy is a lower limit. From the length of the tail, an average velocity of 1125 km s^{-1} is inferred. Equating this to the maximum velocity taken as $1.7 v_b$ gives $t_b \approx 540$ yr, corresponding to $R_{sb} \approx 1$ pc. Although these numbers should not be taken at face value, they nevertheless indicate that the breakout hypothesis is consistent with the observed morphology.

6. CONCLUSION

Using the data from the CGPS we studied the morphology and the environment of the SNR G106.3+2.7 and the pulsar nebula associated with the pulsar J2229+6114 (the “Boomerang”). We conclude that these sources are the result of the same SN event. The SNR morphologically consists of two parts giving the object its cometary shape, in which the tail is due to an outbreak into the interior of a big H I bubble, whereas the head is created by the expanding shock wave interacting with dense ambient material. The kinematics of the associated neutral hydrogen and molecular material, $v_{kin} \sim -6.4 \text{ km/s}$, suggests that both objects are located at the same distance of 800 pc, thereby the SNR is 14 pc long and 6 pc wide and the pulsar nebula has a diameter of 0.8 pc. This close distance is also supported by the presence of high polarized emission.

By studying the energetics of the SNR we found that the “Boomerang” nebula is created by the relativistic wind of the pulsar. For the “Boomerang” we found a spectral index of $\alpha = -0.1$ and $\sim 40\%$ integrated percentage polarization at 1420 MHz. The analysis of the cold environment suggests that the creation of the progenitor star was triggered by stellar wind and/or SN explosions of a group of stars which also created the H I bubble. In this way this is the first detection of a pulsar nebula apparently interacting with its cold environment. It is also an example of a pulsar “displaced” from the center of its associated SNR. In this case, however, the displaced position of the pulsar is not due to high pulsar velocity.

The Dominion Radio Astrophysical Observatory is a National Facility operated by the National Research Council. The Canadian Galactic Plane Survey is a Canadian project with international partners, and is supported by the Natural Sciences and Engineering Research Council (NSERC). SP was supported by NSERC and the Fonds FCAR of Québec. We thank Lloyd Higgs and Tom Landecker for careful reading of the manuscript and discussions.

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FIG. 1.— The SNR G106.3+2.7 at 1420 MHz radio continuum. The H II region S142 is indicated as are the main part of the SNR and the pulsar wind nebula. Contours are at 6.6, 6.8, 7.0, 7.2, 7.5, 7.8, 8.1, 8.4, and 8.7 K in the lower map and from 7 K to 11 K in steps of 0.5 K in the upper image. The resolution is $45''$.

FIG. 2.— Greyscale plot of the polarized emission of the SNR G106.3+2.7 at 1420 MHz. White contours represent the total power radio continuum emission at 1420 MHz. Contour levels are 100, 200, 500, 800, and 1200 mK. Both maps were convolved to a resolution of $2'$ to increase the signal to noise ratio in the polarized intensity map. Contours for the polarized intensity (black) are from 100 mK to 500 mK in steps of 50 mK.

FIG. 3.— Greyscale plots of H I channel maps at low negative velocities with velocities indicated. White contours represent total power radio continuum at 1420 MHz. Both maps were convolved to a resolution of $2'$ to increase the signal to noise ratio in the H I maps.

FIG. 4.— Greyscale plots of CO channel maps at low negative velocities with velocities indicated. White contours, as in Fig. 2, represent total power radio continuum at 1420 MHz. Both maps were convolved to a resolution of $2'$ to increase the signal to noise ratio in the CO maps.

FIG. 5.— Greyscale plot of neutral hydrogen associated with the SNR G106.3+2.7. Overlaid black contours represent molecular material and the white contours (at 200, 500, 800, and 1200 mK) radio continuum at 1420 MHz. All data have been convolved to a resolution of $2'$ to improve the signal to noise ratio. For the neutral hydrogen and the CO the three channels at -5.6 km/s, -6.4 km/s, and -7.2 km/s were averaged together.

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